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AERODYNAMICS NOTE 397

THE SHAPE OF A CABLE USED FOR TOWING A PITOT-STATIC PROBE FROM A HELICOPTER

by

N. E. GILBERT

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(10) N. E. GILBERT

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SUMMARY

The shape of a cable used to tow a pitot-static probe from a helicopter is estimated for airspeeds up to 120 kn. These estimates show the probe to be well outside the influence of the rotor wake. Experimental results obtained from photographs taken from a chase helicopter are used to resolve an uncertainty in cable drag coefficient and comparisons are made with the theoretical predictions of overall shape. The effect of the assumption of a weightless cable and of reduced probe drag are also shown.

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16. *ABSTRACT*

The shape of a cable used to tow a pitot-static probe from a helicopter is estimated for airspeeds up to 120 kn. These estimates show the probe to be well outside the influence of the rotor wake. Experimental results obtained from photographs taken from a chase helicopter are used to resolve an uncertainty in cable drag coefficient and comparisons are made with the theoretical predictions of overall shape. The effect of the assumption of a weightless cable and of reduced probe drag are also shown.

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NOMENCLATURE

a	$(k_c s_1/W)^{-\frac{1}{2}}$
C_D	drag coefficient of probe (based on cross-sectional area of main body, i.e. $\frac{1}{4}\pi d^2$) in direction of flow along probe axis
C_{Dc}	drag coefficient of cable (based on cable reference diameter) in lateral direction of flow
d	probe reference diameter (i.e. of main body)
d_c	cable reference diameter (i.e. of vinyl tubing)
k	$\frac{1}{2}\rho_A(\frac{1}{4}\pi d^2)C_D$
k_c	$\frac{1}{2}\rho_A d_c C_{Dc}$
P	upper end of cable element
P_0	upper end of cable length (i.e. suspension point at helicopter)
P_1	lower end of cable length (i.e. suspension point at probe)
s	distance along cable of P from P_0
S	s/s_1
T	tension force at P
u	horizontal velocity of air relative to cable and probe (positive in x direction), i.e. helicopter airspeed
U	u/a
w	cable weight in air per unit length
W	probe weight in air
xz	cable axes with origin at P_0, z axis vertical (positive downwards), and x axis horizontal in helicopter fuselage plane of symmetry (positive rearward)
x, z	linear displacement coordinates in cable axes
X, Z	x/s_1, z/s_1
α	probe sweepback angle, $\arctan(x_1/z_1)$
δ	denotes increment in quantity prefixed (see Fig. 1)
θ	angular displacement of cable at P from z axis (increases positively towards x axis)
μ	ws_1/W
ν_A	kinematic viscosity of air
ρ_A	air density
τ	T/W

Subscripts

0, 1	value at P_0, P_1

1. INTRODUCTION

In order to validate a mathematical model of the Royal Australian Navy's Sea King Mk.50 helicopter [1], flight trials [2] were conducted during 1979. For some of these trials, a pitot-static probe was towed from the helicopter so that airspeed measuring devices on the helicopter could be calibrated [3]. The probe is of similar design to that developed by ARDU (Aircraft Research and Development Unit, RAAF, Salisbury, South Australia). It was originally developed by the US Navy for the purpose of giving stable flight when towed from a helicopter, but further modifications were made by ARDU to improve stability. For accurate measurements, it was important for the probe to be well outside the influence of the rotor wake. To ensure this, the shape of the cable, and hence position of the probe relative to the helicopter, were estimated theoretically. These estimates, together with the two-dimensional analysis on which they are based, are first presented in this document. In two-dimensional steady state cable problems where gravitational and fluid forces are considered, analytical solutions are possible [4], provided vertical displacement between the cable ends is known. Here, because cable length, rather than vertical displacement, is known, the solution can only be obtained by numerical integration of the differential equations with cable length as the independent variable. In the analysis, there was a fair degree of uncertainty in the value of the cable drag coefficient, C_{Dc}. While this uncertainty was considered unlikely to alter the conclusion that the rotor wake did not affect the probe measurements, it was felt that some validation of the estimates was desirable and would enable more confident predictions if required subsequently. Hence, measurements were made from photographs taken from another helicopter flying alongside, and these were used to determine a value of C_{Dc} which gave the best overall agreement between theoretical and experimental results. Finally, the effect of the assumption of a weightless cable, as in Reference 5, and of reduced probe drag are shown.

2. MATHEMATICAL ANALYSIS

Numerous analysis of towed body configurations have appeared in the literature. One such, which can conveniently be utilised in the present application is given in References 6 and 7, in which a three-dimensional steady state mathematical model of a cable used to suspend a sonar body from a helicopter is derived. The model may be applied here, where the type of solution required is two-dimensional for a uniform fluid velocity. In References 6 and 7, the vertical displacement of the lower end of the cable, z_1, is assumed known and vertical displacement, z, is therefore used as the independent variable. Here, total cable length, s_1, is known so that displacement along the cable, s, is defined as the independent variable. Considering an element of the cable at P (see Fig. 1), the basic equilibrium equations are given by (see Equations (18*a*,*b*,*c*) of Ref. 6)

$$T\frac{d\theta}{ds} = w\sin\theta - k_c u u \cos^2\theta \tag{1}$$

$$\frac{dT}{ds} = w\cos\theta \tag{2}$$

and the cable shape is defined by the relations

$$\frac{dx}{ds} = \sin\theta \tag{3}$$

$$\frac{dz}{ds} = \cos\theta \tag{4}$$

Dimensionless qualities are now introduced as in References 6 and 7, except that z_1 is replaced by s_1, giving $\mu = ws_1/W$, $X = x/s_1$, $Z = z/s_1$, $S = s/s_1$, $\tau = T/W$, and $U = u/a$, where $a = (k_c s_1/W)^{-\frac{1}{2}}$. Equations (1) to (4) may be written in terms of these quantities as

$$\frac{d\theta}{dS} = \frac{\mu \sin\theta - U|U|\cos^2\theta}{\tau} \tag{5}$$

$$\frac{d\tau}{dS} = -\mu\cos\theta \tag{6}$$

$$\frac{dX}{dS} = \sin\theta \tag{7}$$

$$\frac{dZ}{dS} = \cos\theta \tag{8}$$

Unlike the case where Z is the independent variable, an analytical solution of Equations (5) and (6) is not possible. Hence, given $\theta = \theta_1$ and $\tau = \tau_1$ at P_1, Equations (5) and (6) are solved using the Runge-Kutta second order method. The displacements X and Z are calculated from Equations (7) and (8) using Simpson's formula following each step of the Runge-Kutta method used to obtain θ and τ. As described in Appendix A of Reference 6, this procedure is particularly suited to the Runge-Kutta second order method used, since the mid-interval values required by Simpson's formula are directly provided by the Runge-Kutta method. It was found that an integration interval in S of 0·02 gives sufficient plotting accuracy for the curves presented in the figures.

The boundary values, θ_1 and τ_1, are given on resolving in the x and z directions at P_1 (see Fig. 1), i.e.

$$T_1\cos\theta_1 = W \tag{9}$$

$$T_1\sin\theta_1 = k_c u_1|u_1| \tag{10}$$

from which

$$\tan\theta_1 = k_c u_1|u_1|/W \tag{11}$$

$$\tau_1 = \sec\theta_1 \tag{12}$$

3. CABLE AND PROBE PARAMETERS

The dimensions and weights required in the theoretical analysis for both the cable and probe are given in Table 1. Drag coefficients were derived theoretically for the cable and experimentally from wind tunnel tests for the probe as follows.

(a) Cable drag coefficient

The cable consists of a 7 × 7 stainless steel control cable of diameter 2·38 mm (0·00781 ft) and two lengths of vinyl tubing of diameter 5·5 mm (0·018 ft). The three lengths are taped together (see Fig. 1) with the steel cable facing the airflow. Ideally, the drag coefficient of the resulting section is expected to be between that experienced for an elliptic section with chord to thickness ratio of 2·0 and that for a smooth circular cylinder. For airspeeds in the range 20 to 120 kn, the corresponding Reynolds number* range is from $3{\cdot}9 \times 10^3$ to $2{\cdot}3 \times 10^4$, which is subcritical. From Reference 8, the drag coefficients for the elliptic section and circular cylinder are 0·6 and 1·1 respectively. However, there is likely to be some twisting of the taped tubes, thus increasing the effective drag coefficient (based on a fixed reference diameter). To allow for this, a range in drag coefficient, C_{D_c}, of between 0·9 and 1·5 is assumed.

* Reynolds number = ud/ν_1, where $\nu_1 = 1{\cdot}452 \times 10^{-5}$ m²/s ($1{\cdot}563 \times 10^{-4}$ ft²/s).

TABLE 1

Cable and Probe Dimensions and Weights

Quantity	Value
Cable reference diameter, d_c	5·5 mm (0·018 ft)
Cable weight per unit length,* w	0·588 N/m (0·0402 lbf/ft)
Cable length, s_1	45·7 m (150 ft)
Probe reference diameter, d	38·1 mm (0·125 ft)
Probe weight, W	64·1 N (14·4 lbf)
Length of probe ahead of cone	1·14 m (3·73 ft)
Cone base diameter	0·305 m (1·00 ft)
Cone vertex angle	90°
Diameter of holes on cone	19·1 mm (0·0625 ft)
Distance of centre of hole from cone edge:†	
(i) outer row	25·4 mm (0·0833 ft)
(ii) inner row	38·1 mm (0·125 ft)

* Weight per unit length of steel cable = 0·234 N/m (0·0160 lbf/ft)
Weight per unit length of vinyl tubing = 0·177 N/m (0·0121 lbf/ft)
$w = 0{\cdot}234 + 2 \times 0{\cdot}177 = 0{\cdot}588$ N/m (0·0402 lbf/ft)

† Two rows of equally spaced holes (22 for outer row; 18 for inner row).

(b) Probe drag coefficient

Photographs have been taken of the probe when freely suspended by a short length of cable in the ARL 2·7 × 2·1 m (9 × 7 ft) low speed wind tunnel (see Fig. 2). The deviation, θ_1, of the cable from the vertical at the probe was measured from the photographs. At all airspeeds, the probe was tilted at about 1° nose down. In the calculations below, this angle was assumed zero. The probe drag coefficient, C_D, may be calculated using Equation (11), where $k = \frac{1}{2}\rho_A(\frac{1}{4}\pi d^2)C_D$ and $\rho_A = 1{\cdot}226$ kg/m³ (0·002378 slug/ft³). Hence,

$$C_D = \frac{W \tan\theta_1}{\frac{1}{2}\rho_A(\frac{1}{4}\pi d^2)u^2} = 3{\cdot}46 \times 10^5 \frac{\tan\theta_1}{u^2} \qquad \text{for } u \text{ in knots}$$

Because of the possibility of fitting a different probe tail (see below), it was decided to base, probe drag coefficients on the cross-sectional area of the main body, which would be unaffected by any such change, rather than on that of the tail cone base. The results are given in Table 2. A mean value for C_D of 44·0 is assumed, which is equivalent to a value of 0·69 based on the cone base area.

TABLE 2

Probe Drag Coefficient from Wind Tunnel Tests

Photo no.	u (kn)	θ_1 (deg)	C_D
1	41·3	12·3	44·2
2	51·4	18·8	44·5
3	70·7	32·6	44·2
4	96·5	50·8	45·5
5	117·1	59·7	43·1

4. RESULTS

Figure 3 shows the predicted cable shapes for airspeeds of 40, 80, and 120 kn and for values of C_{Dc} in the range 0·9 to 1·5. Also shown are estimates of the forward boundary of the rotor wake at airspeeds of 20, 40 and 80 kn. In the absence of suitable experimental data, the boundaries were obtained from simulations using ARL's Sea King mathematical model [1]. In the model, the rotor wake vortex distribution is approximated by a straight elliptic cylinder as given in Reference 9. For the simulations, the rotor radius is 9.46 m (31.0 ft) and the helicopter weight is assumed to be 84·6 kN (19 000 lbf). It can be seen in Figure 3 that, even for the highest value of C_{Dc} assumed, the probe is well outside the rotor wake for airspeeds between 20 and 120 kn.

To determine a value of C_{Dc} more precisely, measurements were made from photographs taken from another helicopter flying alongside (see Fig. 4). The cable and probe were observed to remain fairly steady in flight with only very small cable oscillation. When the photographs were taken, the main consideration was to confirm that the probe was well clear of the influence of the rotor wake and was steady in flight. Accurate determination of the cable shape was a secondary consideration. Therefore, no special care was taken to minimize parallax errors. On viewing the position of the horizon and orientation of the helicopter on the photographs, it was considered that, in general, tilt in the vertical plane was likely to be larger than that in the horizontal plane. Provided the probe sweepback angle is not too large (i.e. not close to 90°), this will generally result in larger parallax errors in the vertical plane. Hence, error estimates were first made for the vertical plane, and, since these showed that the corrections required were mostly insignificant, corresponding estimates were not made for the horizontal plane. In the worst case, vertical tilt angle was estimated to be 9°, which, for a vertical angular displacement of the image of the cable of 15°, resulted in a parallax error of 3·5%. Errors arising from lens distortion were not considered significant. Airspeed indicated by the aircraft instrumentation was corrected from measurements taken from the trailing probe [3]. Figure 5 shows a comparison between experimental (i.e. from the photographs) and theoretical values of probe sweepback angle, α. The theoretical values are given for values of C_{Dc} between 0·9 and 1·5. The low experimental value at 42 kn is possibly due to an unusually significant parallax error in the horizontal plane, which could have occurred because, when the photograph was taken, the chase helicopter was positioned well behind the helicopter with the probe. Hence, allowing for this uncertainty, a value for C_{Dc} of 1·3 was chosen as giving the best overall agreement between theoretical and experimental results. Using this value, a comparison between theoretical and experimental values of cable angle at the helicopter, θ_0, and at the probe, θ_1, is shown in Figure 6, where agreement is observed to be good. Figure 7 shows the corresponding comparison for cable shape.

In Reference 5, estimates of cable shape are given for a weightless cable, thus enabling an analytical solution. In Figure 8, it can be seen that for the system described here there is a significant, but fairly uniform, difference in cable shapes obtained with and without this assumption. Since the assumption gives results showing the probe to be closer to the rotor wake boundary, weightless cable results could be used as a conservative guide to the likelihood of interference of the rotor wake.

Before undertaking the present study, the possibility of replacing the probe tail cone with a cruciform finned tail was considered. The purpose of this was to reduce the probe drag so that the cable would remain closer to the vertical. Figure 9 shows the effect of reductions in probe drag coefficient by factors of a half and quarter. It can be seen, especially at higher airspeeds, that the main effect is to make the cable at the probe closer to the vertical, while not significantly reducing the probe sweepback angle. A reduction in cable drag would have a much more significant effect.

5. CONCLUDING REMARKS

Theoretical estimates of the shape of a cable used to tow a pitot-static probe from a helicopter have been presented for airspeeds up to 120 kn. These estimates show the probe to be well outside the influence of the rotor wake. Measurements made from photographs taken from a chase helicopter are used to obtain a more specific value of cable drag coefficient within the range initially assumed from theoretical considerations alone. Using this value, overall agreement between experimental (i.e. from photograph measurements) and theoretical estimates of

cable shape is observed to be good. Results obtained assuming a weightless cable show the probe to be closer to the rotor wake boundary and hence may be used as a conservative guide to the likelihood of interference of the rotor wake. Replacement of the probe tail cone with a low drag cruciform finned tail, while making the cable at the probe closer to the vertical, does not reduce the sweepback angle significantly. To produce a significant effect, a cable with lower drag would be needed.

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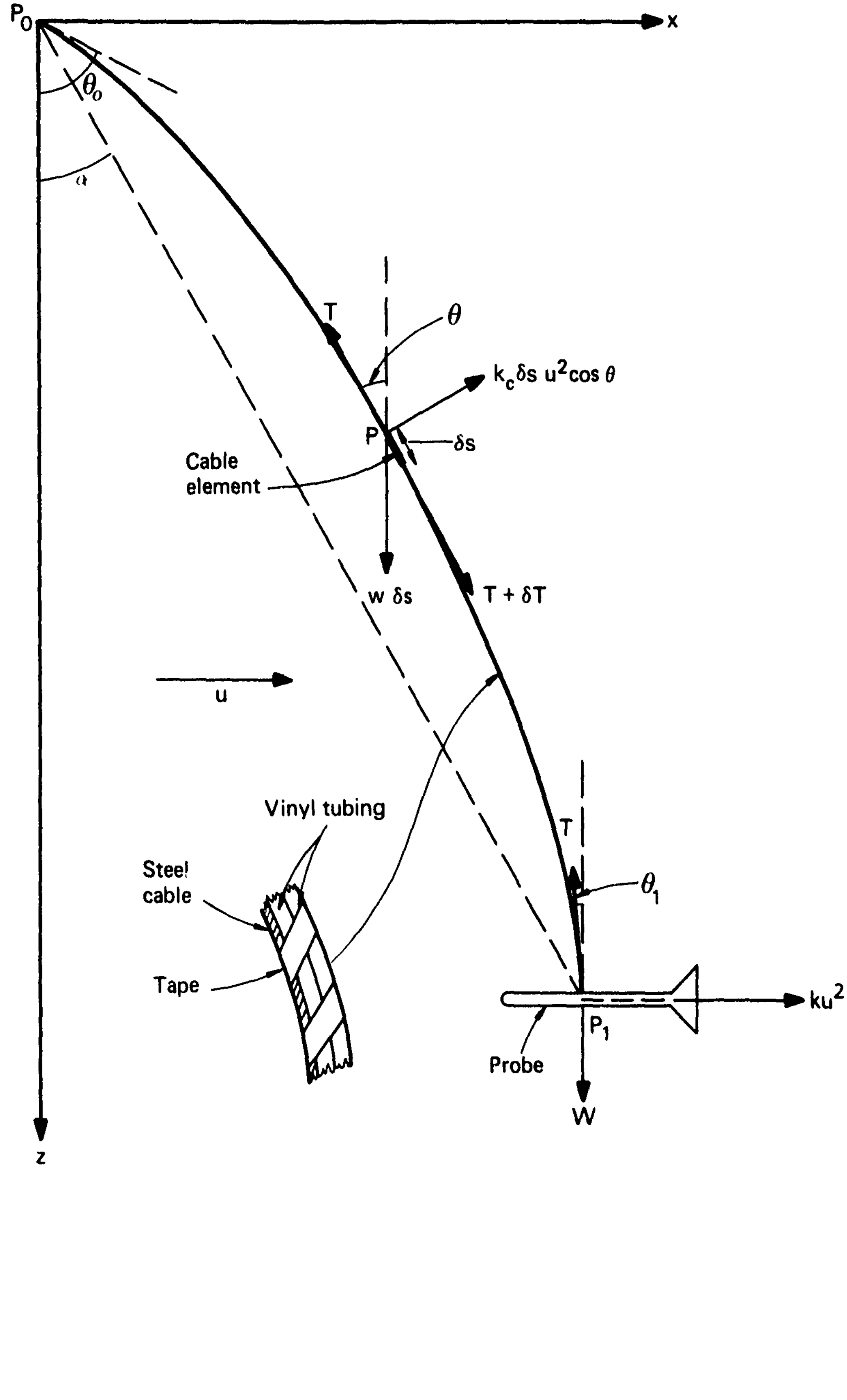

FIG. 1 FORCES ACTING ON CABLE ELEMENT AND PROBE

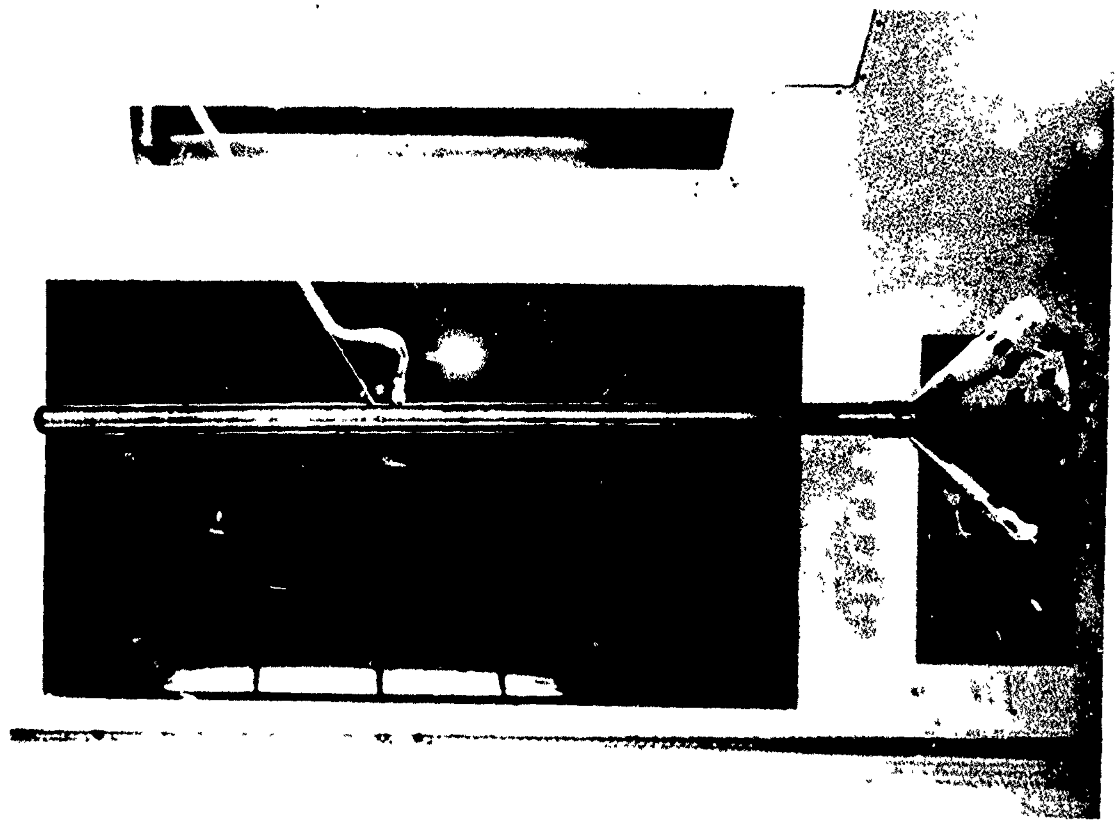

FIG. 2 PROBE FREELY SUSPENDED IN WIND TUNNEL

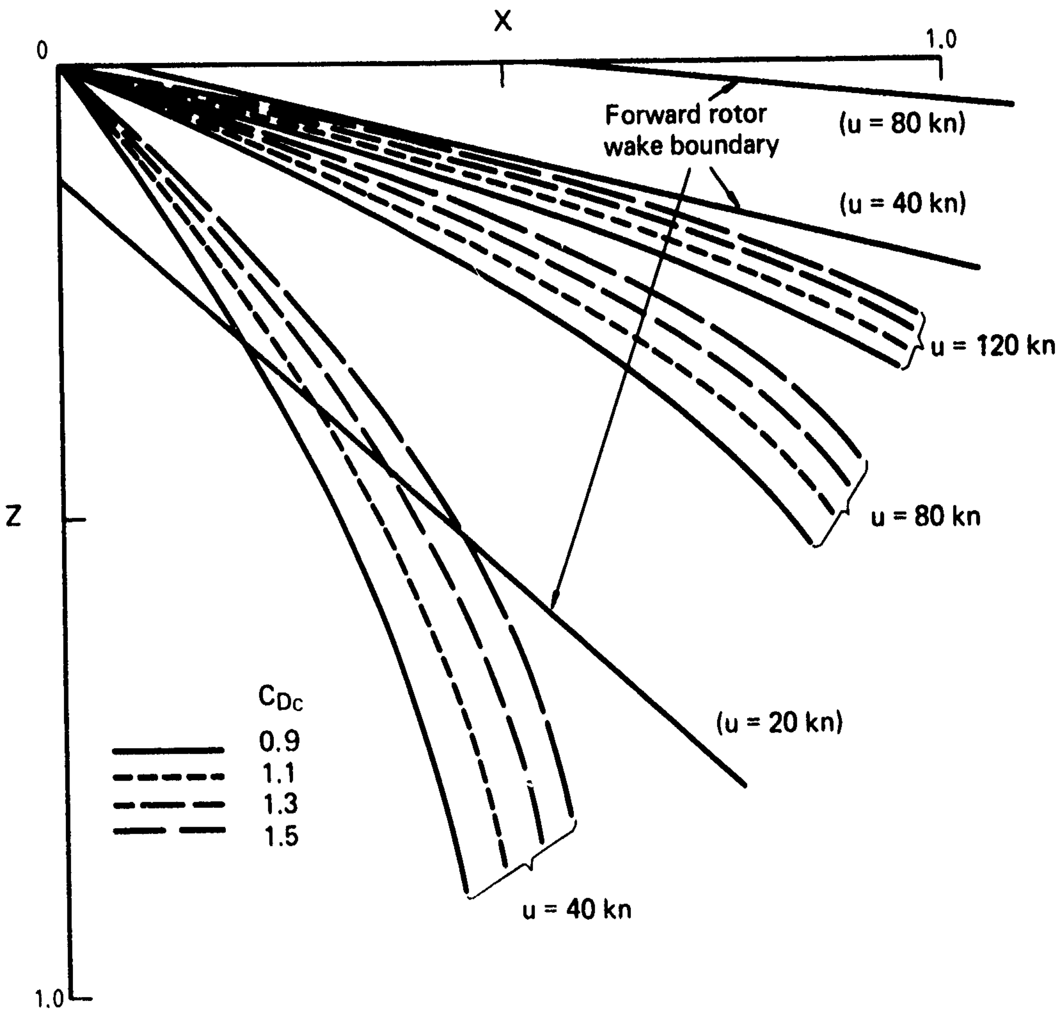

FIG. 3 PREDICTED CABLE SHAPES AND FORWARD ROTOR WAKE BOUNDARIES

FIG. 4 PROBE TOWED FROM HELICOPER; IMAGE OF CABLE IS ENHANCED

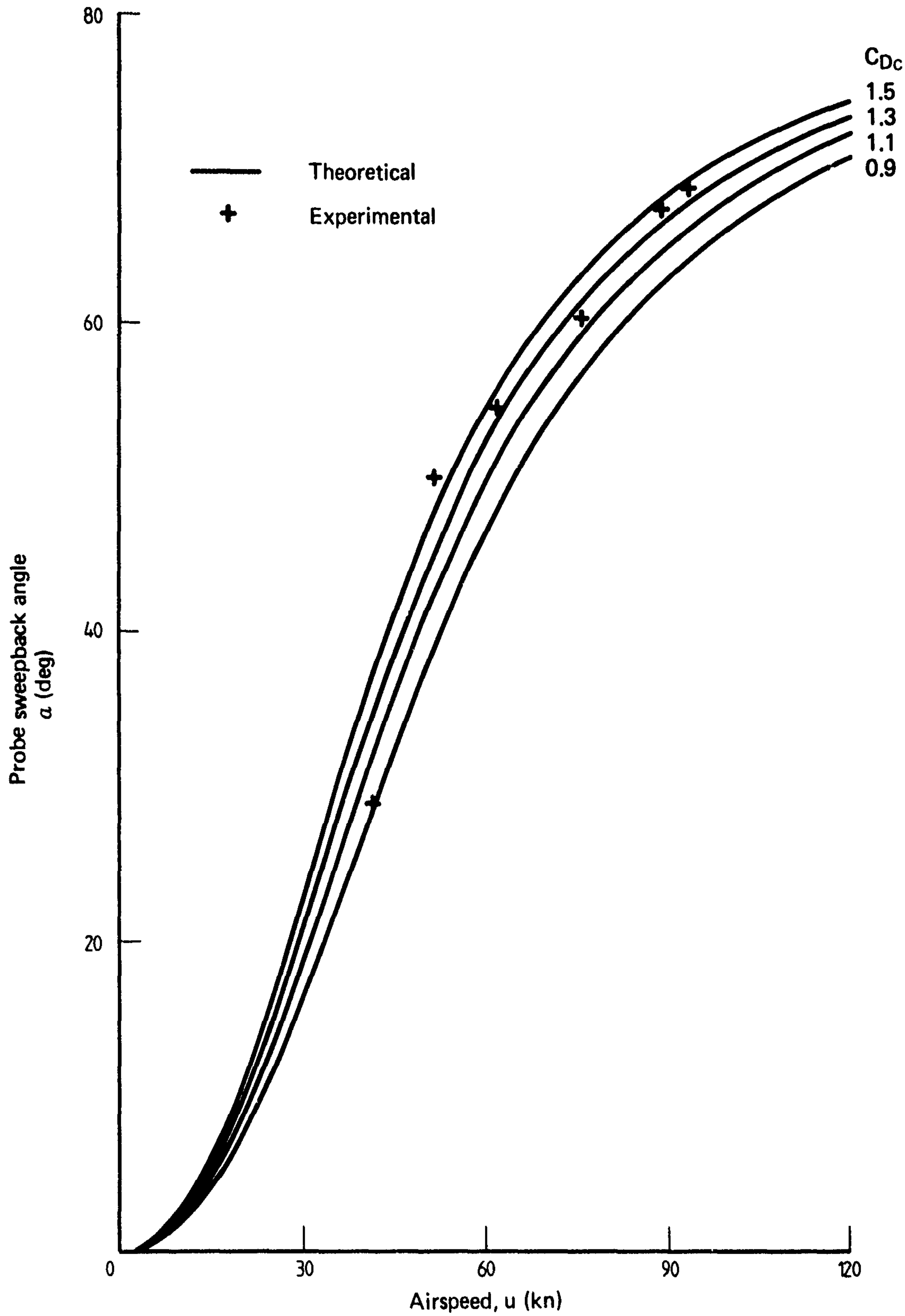

FIG. 5 COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL VALUES OF PROBE SWEEPBACK ANGLE

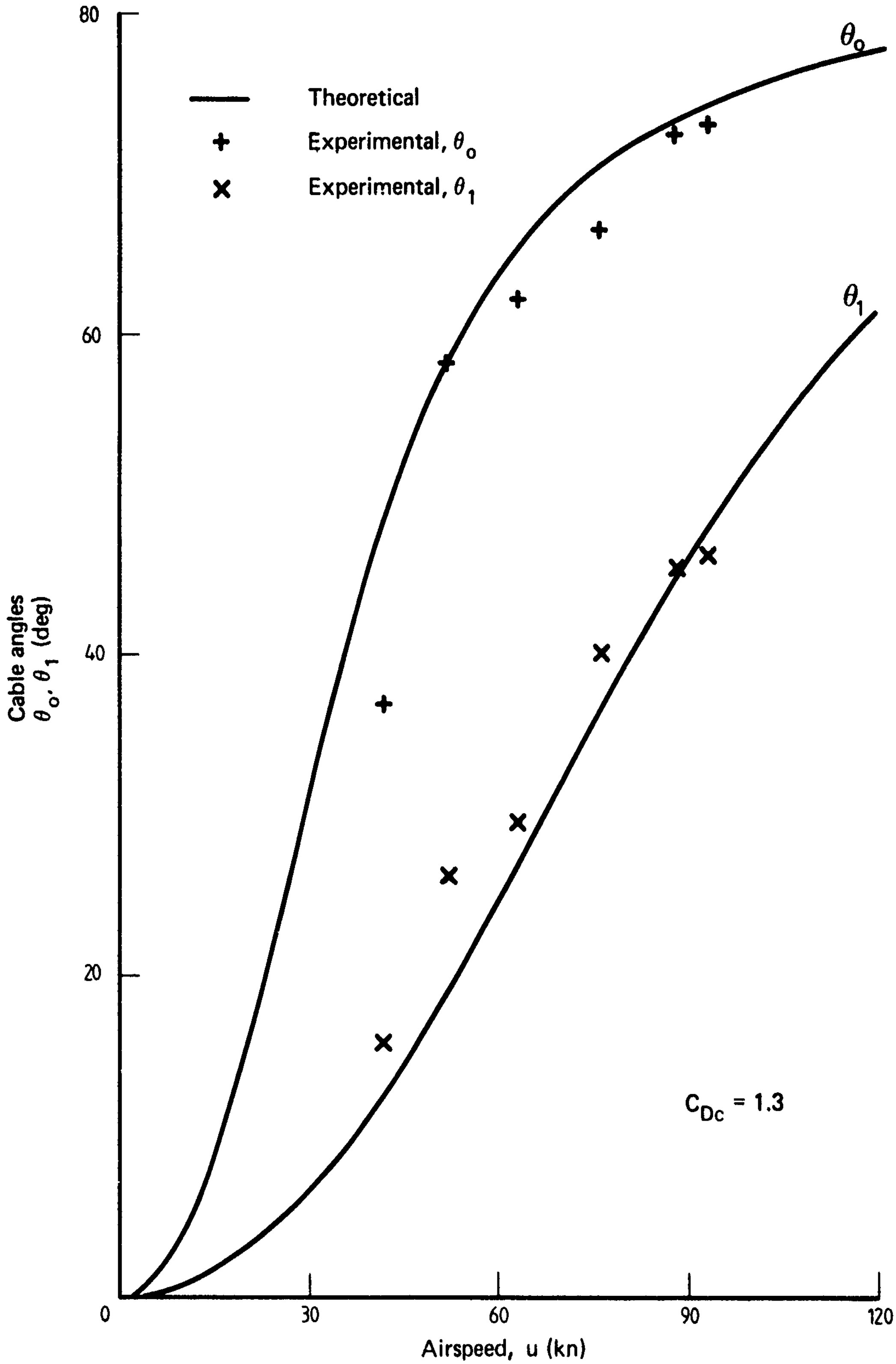

FIG. 6 COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL VALUES OF CABLE ANGLE AT HELICOPTER, θ_o, AND AT PROBE, θ_1

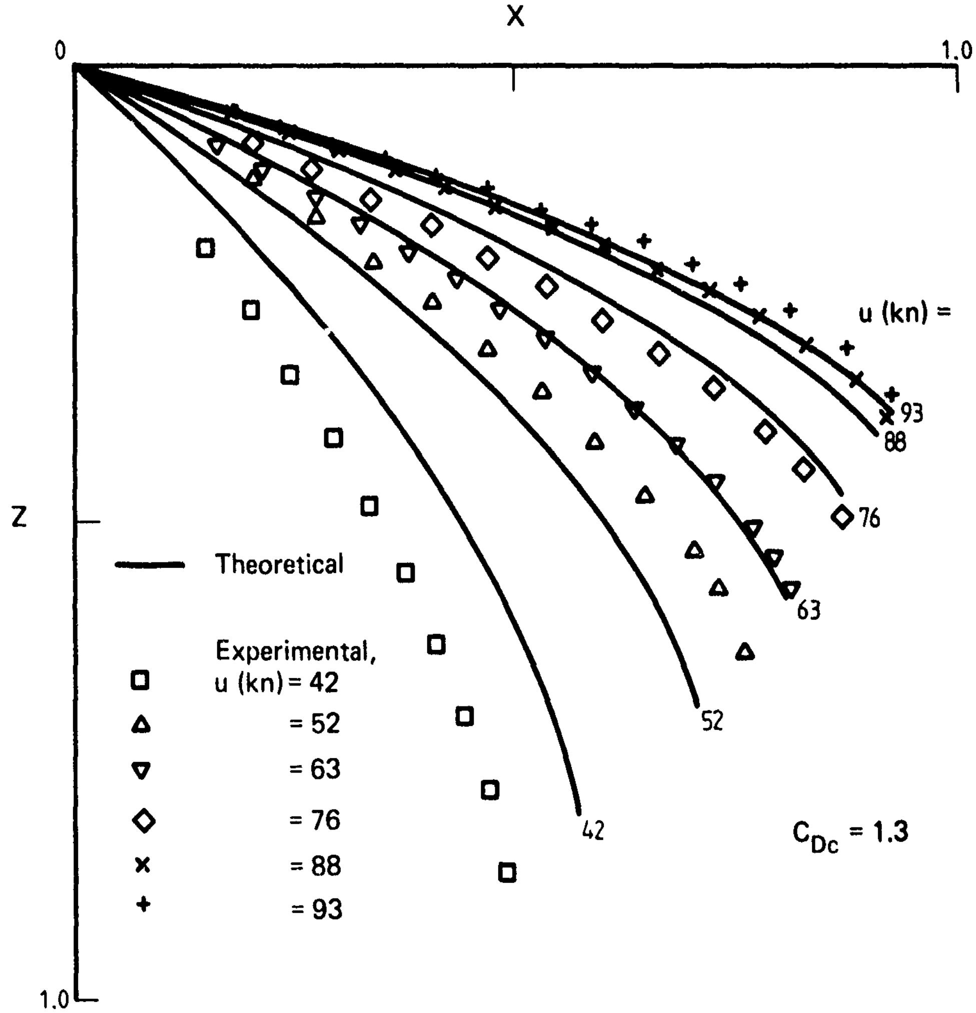

FIG. 7 COMPARISON BETWEEN THEORETICAL AND EXPERIMENTAL CABLE SHAPES

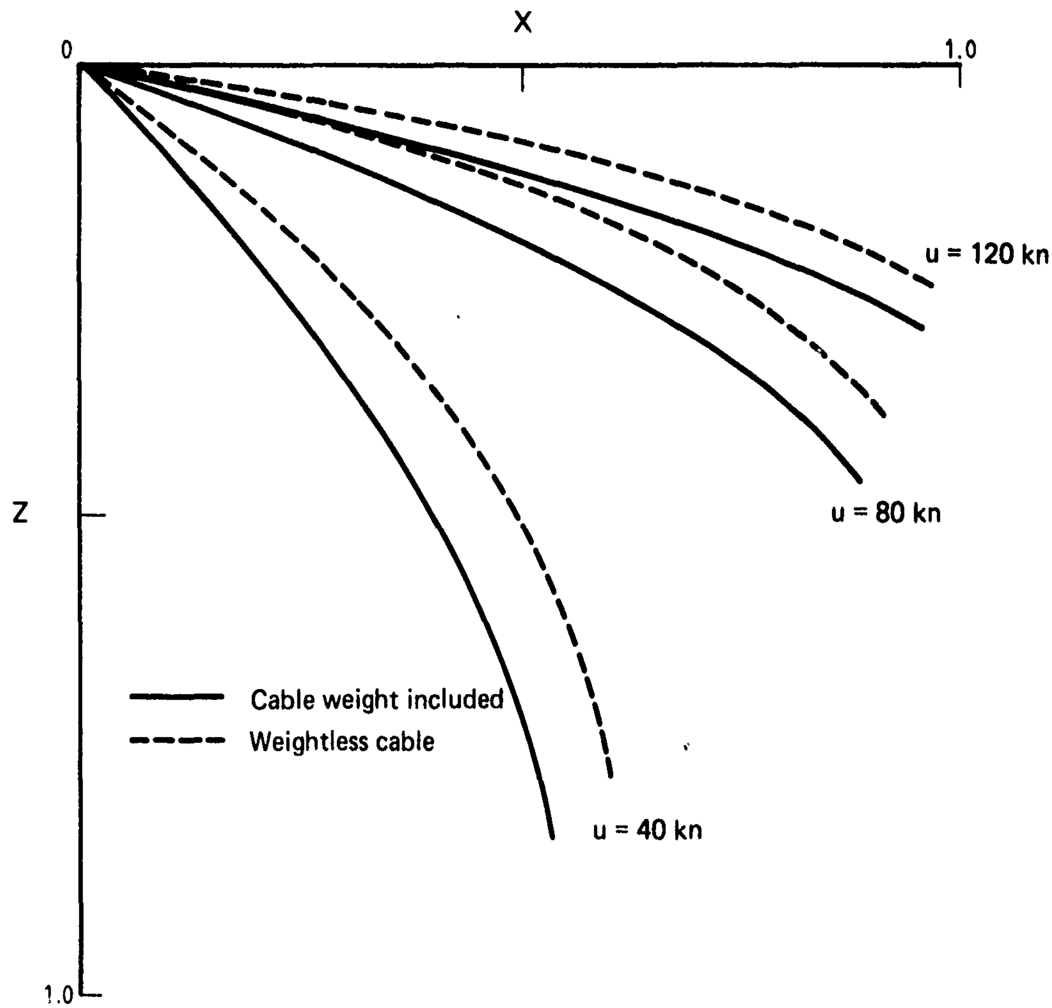

FIG. 8 EFFECT OF WEIGHTLESS CABLE ASSUMPTION ON CABLE SHAPE

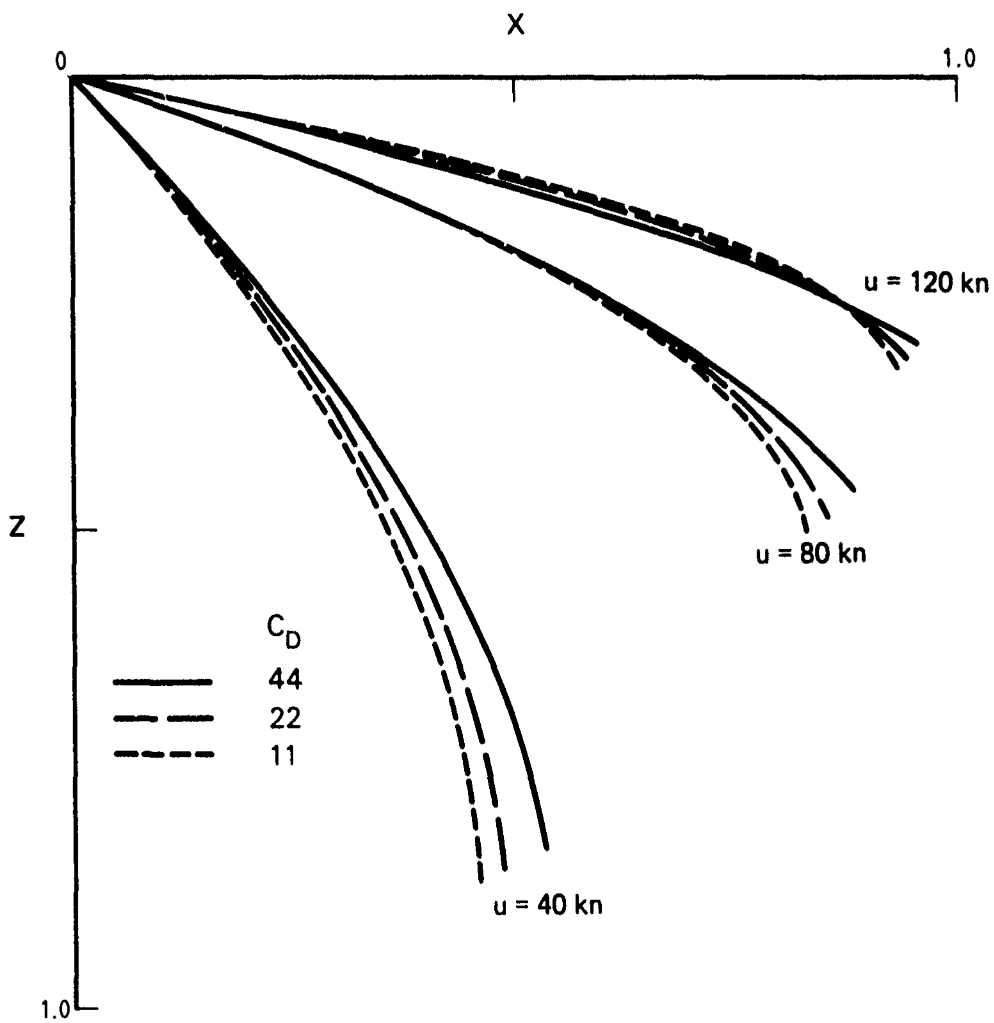

FIG. 9 EFFECT OF REDUCED PROBE DRAG ON CABLE SHAPE

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